Summary of Preliminary Analysis of Historical Stratification in South San Francisco Bay
Mark Stacey, UC-Berkeley
December 2014

The hydrodynamics of South San Francisco Bay are known to force the system into and out of a stratified state, with the belief that the annual cycle of freshwater flows and the spring-neap cycle of the tides dominate the variability. The strength and duration of a stratification event is an important driver of ecosystem variability, due to the associated reduction in vertical mixing. Reduced vertical exchanges lead to retention of phytoplankton in the upper water column, providing improved light conditions and separation from benthic grazers; they also reduce the vertical fluxes of dissolved oxygen to the lower water column, increasing the risk of hypoxic conditions.

In spite of its perceived importance to the South Bay ecosystem, stratification in South Bay has received very little focused study. In the analysis described here, we perform a preliminary analysis of stratification in South Bay using historical data to establish the frequency, magnitude and duration of stratification events. Specifically, we will develop metrics to describe the persistence of stratification events and then use a simple analytical scaling to evaluate the likelihood of longer stratification events under future conditions.

Data Overview

The data used in this study were collected by the U.S. Geological Survey at their San Mateo Bridge location (Figure 1). This mooring includes top (13.4 meters above the bottom) and bottom (3 meters above the bottom) conductivity-temperature-depth sensors, and has been active from 1990 through the present, with the exception of approximately a 2 year gap in 1999-2001. The data streams from the USGS were of high quality, and required no additional quality control, although there is one period in 2001 when the calibration of the two sensors seem somewhat inconsistent (showing inverted stratification in late 2001), but that period does not affect the analysis presented here.

The top-bottom salinity difference was calculated by directly differencing the two timeseries; the resulting record of stratification is shown in Figure 2. Strong annual and inter-annual variability is clearly evident, with strong stratification events typified by vertical salinity differences greater than 5 psu occurring during the wet season, but not in all years. Of particular note are the series of strong, persistent events in the period 1995-1998 and the lack of events in the period 2007-2010.

To examine the timing and duration of these stratification events, we separate the data record by calendar year in Figure 3. In this figure, it is clear that major stratification events occur only in the period from January to early May, and individual events can be of duration of a week or longer. The color-coding in Figure 3 is by calendar year and, although it is not possible in this figure to determine which year is which, it is clear that some years are characterized by regular strong events while others have limited or no events of note.

Stratification Statistics

Our goal is to understand the frequency and duration of stratification events in South Bay, which requires the specification of a threshold for the water column to be considered “stratified”. The impact of this threshold is illustrated in Figure 4, which shows the stratification timeseries from March and April of 1998. The green and red bars show the duration of a stratification event with thresholds of 2 psu and 0.25 psu respectively, and illustrate how the assumption of a stratification threshold can alter the statistics of the frequency and duration of the events. In this particular example, a 2 psu threshold results in the March 6 – March 26 period being divided into 2 separate stratification events, each of approximately 8 days duration. With a threshold of 0.25 psu, on the other hand, the period has a single stratification event with duration of 20 days. The choice of a threshold requires a subjective evaluation of the results: a lower threshold results in fewer, but longer, stratification events while a higher threshold results in more, but shorter, events.

To specify the stratification threshold, we wanted to ensure that the threshold is both above the detection limit and dynamically significant. Examining the two salinity timeseries, and comparing with available Polaris CTD profiles, we concluded that 0.5 psu was a minimum threshold to meet these criteria. To be slightly more conservative, we chose a threshold of 0.75 psu. The results for the March-April 1998 period are illustrated in Figure 5, which shows the period being divided into 4 significant stratification events (as well as many more very short ones that are not highlighted in the figure). These four events ranged from 3.5 to 9 days, and all four had stratification that greatly exceeded the 0.75 psu threshold.

Extending this threshold analysis to the entire data record allows us to count the number of events of particular duration. This frequency analysis would allow us to define the “return period” of particular stratification events in the same way as is done for flood forecasts, although the 20 year record here is not long enough to establish converged statistics. Nonetheless, the frequency distribution of stratification events is shown in Figure 6, which simply presents the number of events (height of bars) of a given duration (horizontal axis, in hours). The two left-most bars represent stratification events of less than 12 and 24 hours, which represent tidally-periodic stratification events that are not relevant to the analysis here. In this 20 year record, only 1 event exceeded 240 hours, but 6 events were in the range between 168 and 240 hours. It is therefore not abnormal to have a significant stratification event of duration 7 days or longer, and the “20-year event” is approximately 12 days.

Temperature Stratification

In particular HAB events, it has been noted that temperature stratification was associated with the HAB. In order to consider the role that temperature stratification plays in persistent stratification events, we repeated the analysis described in the previous section, but considering temperature instead of salinity. In Figure 7, the annual variation of temperature stratification is shown, again color-coded by year (as in Figure 3). Temperature stratification events are associated with the spring months, when air temperatures begin to warm, but salinity stratification is still present. Once salinity stratification is reduced in the summer (see Figure 3), temperature stratification events are also reduced. Our interpretation is that the temperature stratification is a *response* to the combined effects of salinity stratification (which reduces vertical mixing) and atmospheric warming.

To confirm that temperature is not an important driver of persistent stratification events, Figure 8 presents the USGS San Mateo Bridge data in T-S space, with temperature difference on the vertical axis and salinity difference on the horizontal. There is a general upwards trend, with increasing temperature stratification associated with increasing salinity stratification (with slope that varies between events, probably due to differences in air temperature). More importantly, the green line shows the level of temperature stratification that would be required for the temperature to effect density stratification at a level comparable to salinity. In all of the persistent events identified in either the salinity or temperature record, the data falls well below this line, which means salinity dominates the density dynamics.

We conclude that temperature is not an important driver of persistent water column stratification, although it should be noted that temperature stratification that is above the upper USGS sensor would not be detected, and may be playing an additional role in shaping the South Bay ecosystem.

Drivers

With the stratification events identified using the 0.75 psu threshold, we performed preliminary analysis of what the key external drivers were in creating persistent stratification events in South Bay. The data were aggregated by Water Year (October 1 through September 30), which meant that a variety of metrics were possible to describe the stratification including maximum event duration, the total time spent stratified, number of events greater than a particular duration and others. In Figure 9 (panels c and d), we present two of these metrics as a function of water year: maximum event duration in a water year and the number of events longer than 24 hours. Regardless of which stratification metric we used, we found that local precipitation, as measured in San Francisco, was the best predictor. In the top panels of Figure 9, this precipitation data is aggregated across the entire water year (panel a) and for the period October-January (panel b). It is clear in this comparison of timeseries that persistent stratification events are associated with increased local precipitation; they are not as strongly correlated with the major freshwater flows into the Bay, which are dominated by Sierra snowmelt.

As a preliminary evaluation of the relevant drivers for persistent South Bay stratification events, we present a direct comparison of the two precipitation metrics with the stratification metrics in Figure 10. Here, the stratification response metrics (maximum event duration within a water year in the upper panels; total time in events longer than 24 hours within a water year in the lower panels) are directly compared to the precipitation data (total water year precipitation in the left panels; early water year precipitation in the right panels). Although not quantified, there is a better positive correlation between South Bay stratification events and early season precipitation than with total water year precipitation.

Our interpretation of this result is that it is local freshwater flows into South Bay, which are strongly forced by local precipitation, that drive persistent, strong, stratification events in South Bay. These flows can have the largest effect on stratification early in the season, when the South Bay is still relatively saline. In the late spring and summer, large flows entering the Bay through the North Bay and Delta freshen the entire Bay to some extent, including South Bay, so that late season precipitation events have a weaker effect on the local stratification. A more complete evaluation of this dynamical description would require additional analysis, including idealized and realistic modeling and would benefit from a longer data record to more completely evaluate a range of conditions and forcing.

Future Conditions

Finally, we wish to explore the prospects for a significant change in the frequency or duration of stratification events under the influence of climate change. The balance between stratifying and destratifying forces is captured by the Simpson number:

$Si = BH/u*^3$

In this expression, B represents the stratifying influence of freshwater flows and the associated density gradients; $u*^3/H$ is the destratifying effects of tidal mixing. In the coming century, both B and u* may be modified, either through changes in precipitation or in tidal forcing (due to the combined effects of sea level rise and new inundation).

To examine how much adjustment from current conditions would be required to create significant changes in the stratification regime, we present in Figure 11 the tidal velocity cubed from observations at the San Mateo Bridge location (the data is from September, but tidal forcing is similar in March), including both the instantaneous (blue) and tidally-averaged (red) currents. The top panel shows current conditions, with the 20-year event (12 day duration) illustrated with the green bars. The idea is that as tidal mixing decreases into the neap tides, it drops below some threshold and the water column stratifies (the start of the green bars); the stratification then persists until the tidal mixing increases to the point that the water column is mixed (the end of the green bars). The upper green bar illustrates this dynamic based on the instantaneous currents; the lower green bar is based on the tidally-averaged currents.

In the lower two panels, we present schematically where this threshold would be if there is a 5% (panel b) and 10% (panel c) adjustment in the relative strength of tidal mixing as compared to buoyancy. That is, panel b represents the case where tidal currents decrease by 5% or buoyancy forcing increases by 16% (because the Simpson number depends on the velocity cubed but is linear with buoyancy). Panel c represents the case where tidal currents decrease by 10% or buoyancy forcing increases by 37%. In each case, it is clear that the 20-year stratification event would increase in duration significantly (consider extending the green bars left and right until they intersect with the velocity data), and in the case of a 10% reduction in the tidal currents, the stratification may persist across the spring tides as well as the neaps, leading to stratification that will vary with freshwater flows, rather than the spring-neap cycle.

Summary

In summary, we found that strong, persistent stratification is common in South Bay, with regular events of magnitude greater than 5 psu that extend for 7 or more days. At the same time, the historical record does not include events that last longer than 12 days, although this may not be the case under future conditions. The key drivers of stratification appear to be early-season local precipitation, although this conclusion would require further analysis to establish it firmly.

It is important to note that this analysis is limited to the central portion of South Bay. The paucity of data in the Lower South Bay (south of the Dumbarton Narrows) made it impossible to evaluate the variation and dynamics of stratification there, and it is quite possible that longer-duration events are more typical in that embayment.

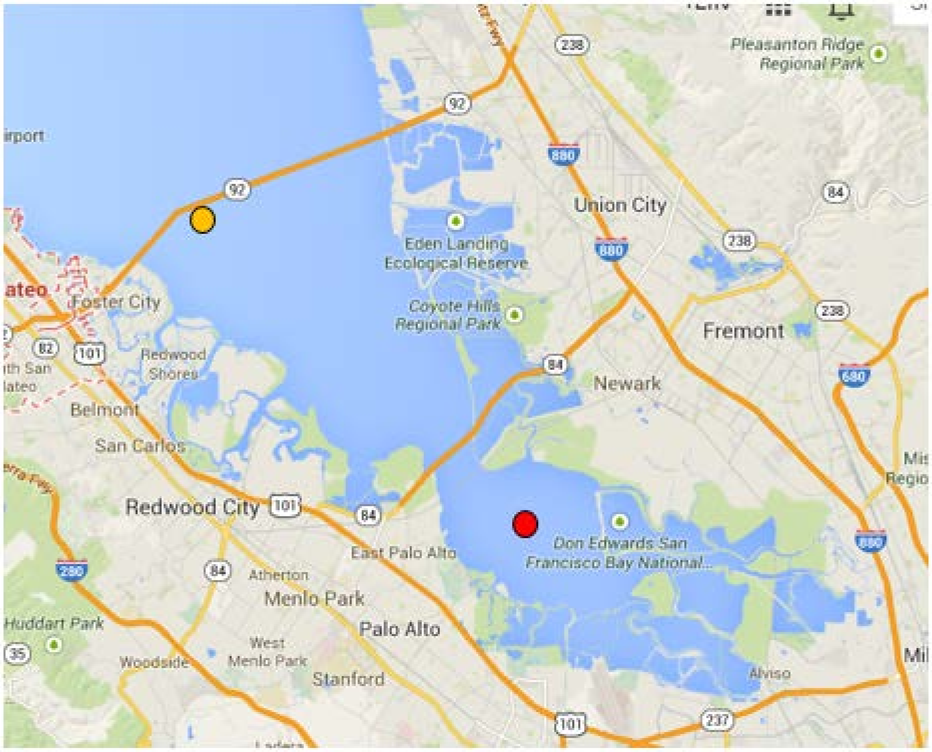

Figure 1: Locations of data sets used in analysis. USGS long-term (1990-present) San Mateo Bridge mooring location marked by yellow marker. Short-term record from lower south bay (red) was found to be of insufficient length or quality for detailed stratification analysis.

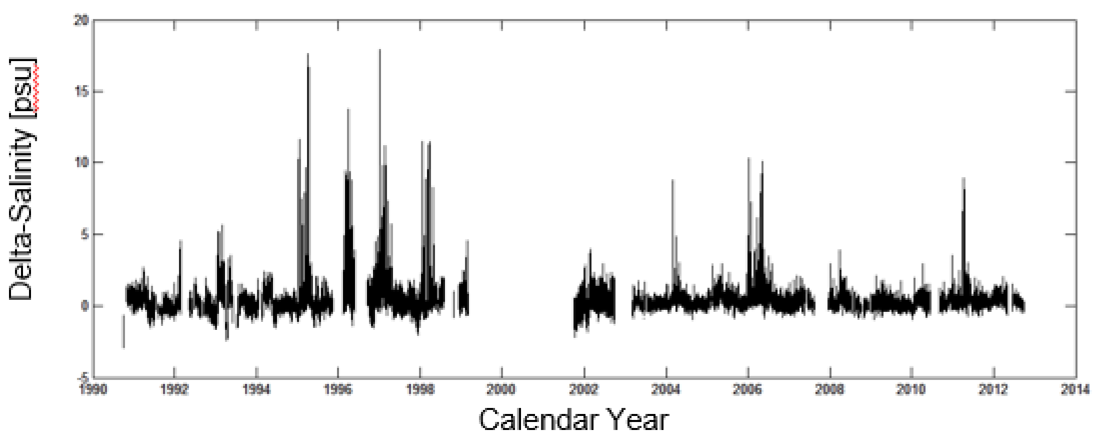

Figure 2: Overview of stratification record at USGS San Mateo Bridge mooring; calculated as bottom salinity minus top salinity

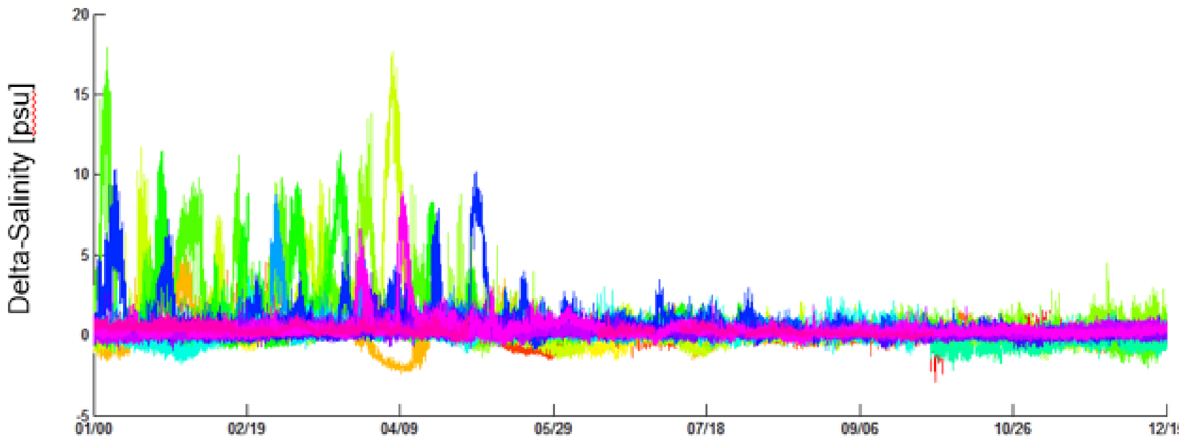

Figure 3: Overview of San Mateo Bridge stratification timeseries as a function of the day of the year, color coded by calendar year.

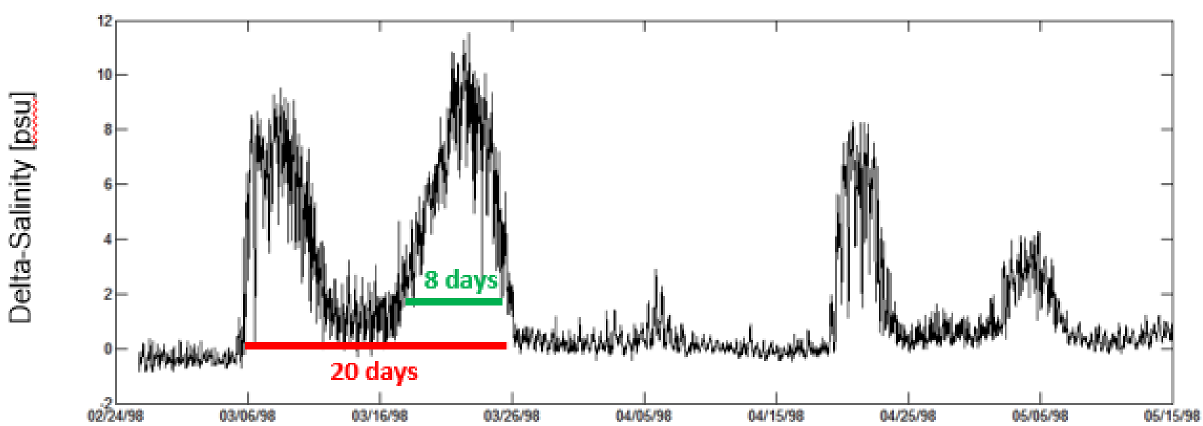

Figure 4: Example of stratification event from March-April 1998. Green and red bars indicate lengths of 8 and 20 days, respectively.

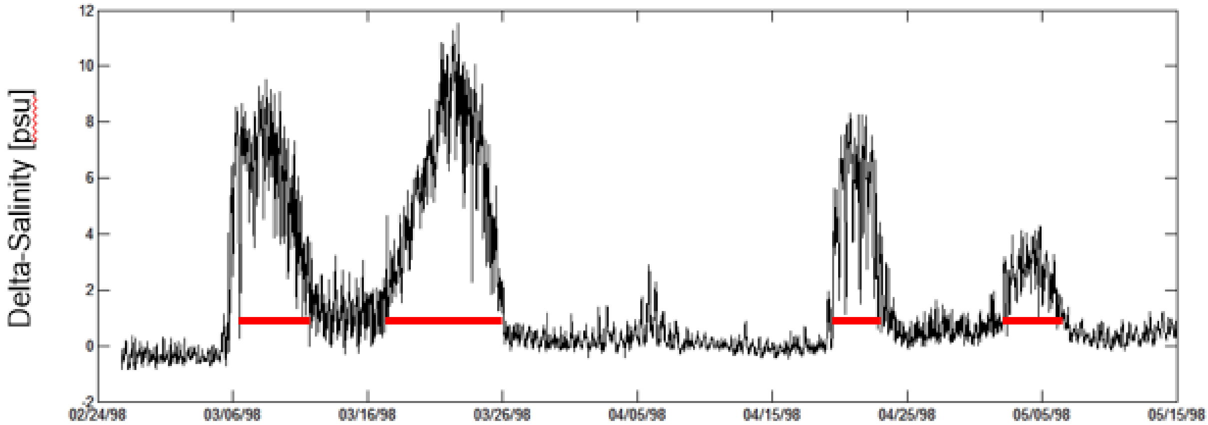

Figure 5: March-April 1998 stratification illustrating 0.75 psu threshold

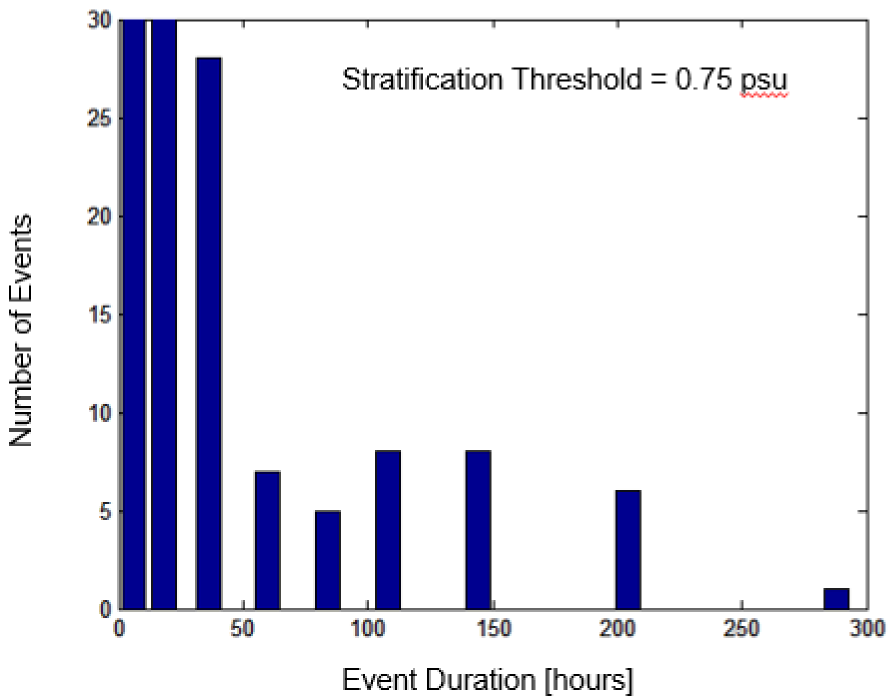

Figure 6: Number of events in stratification record (20 years of data) of a given duration.

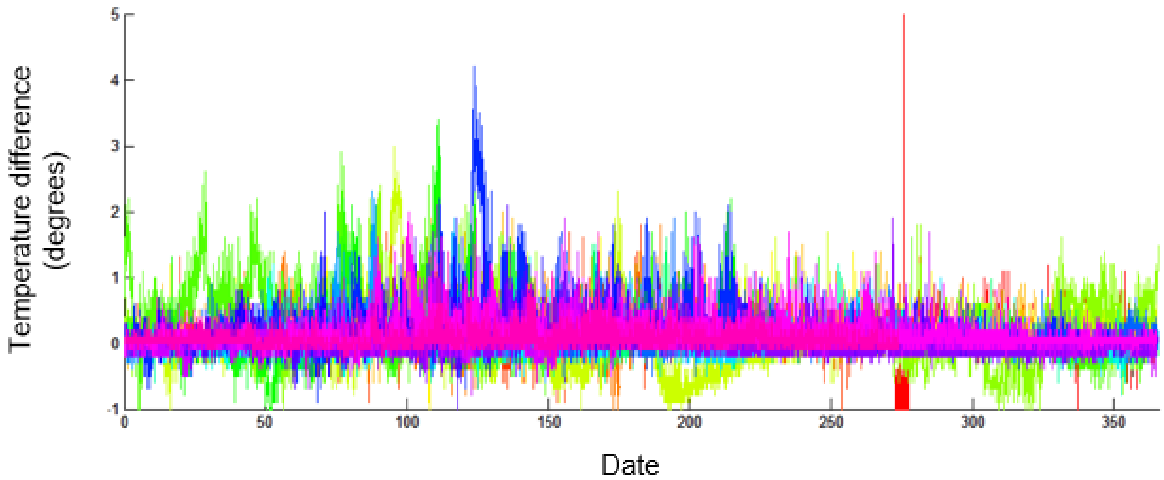

Figure 7: Annual variability of top-bottom temperature difference, color-coded by year (as in Figure 3)

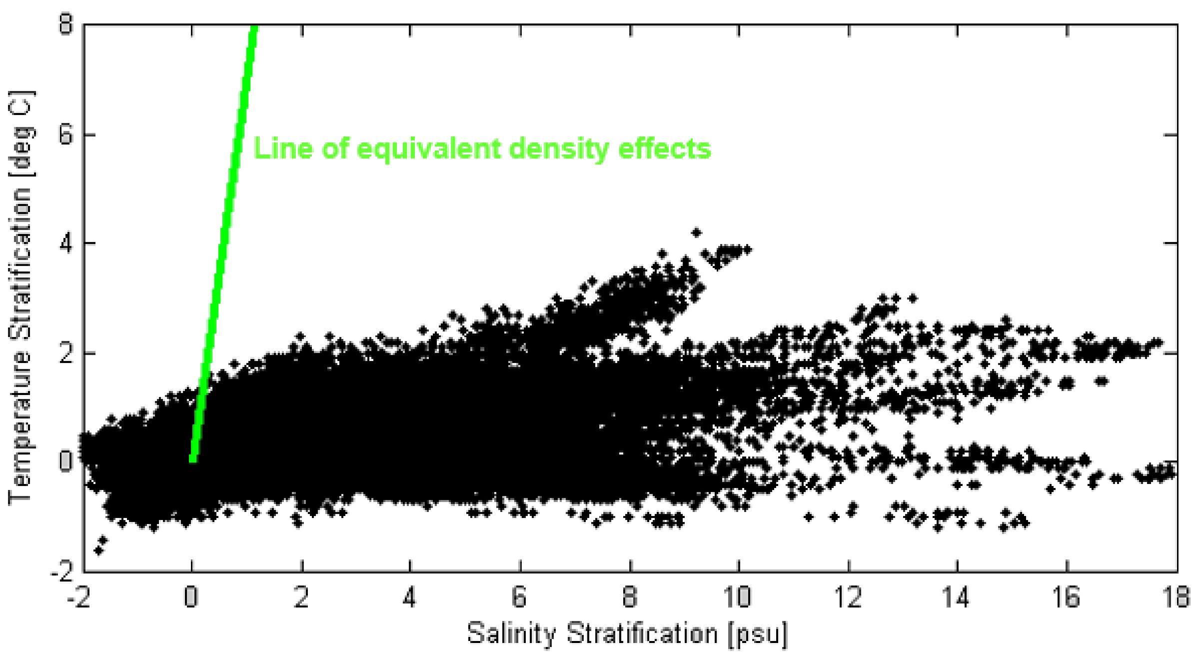

Figure 8: Comparison of salinity and temperature effects on stratification. Data is shown as black dots in T-S space; Green line shows equivalent density effects

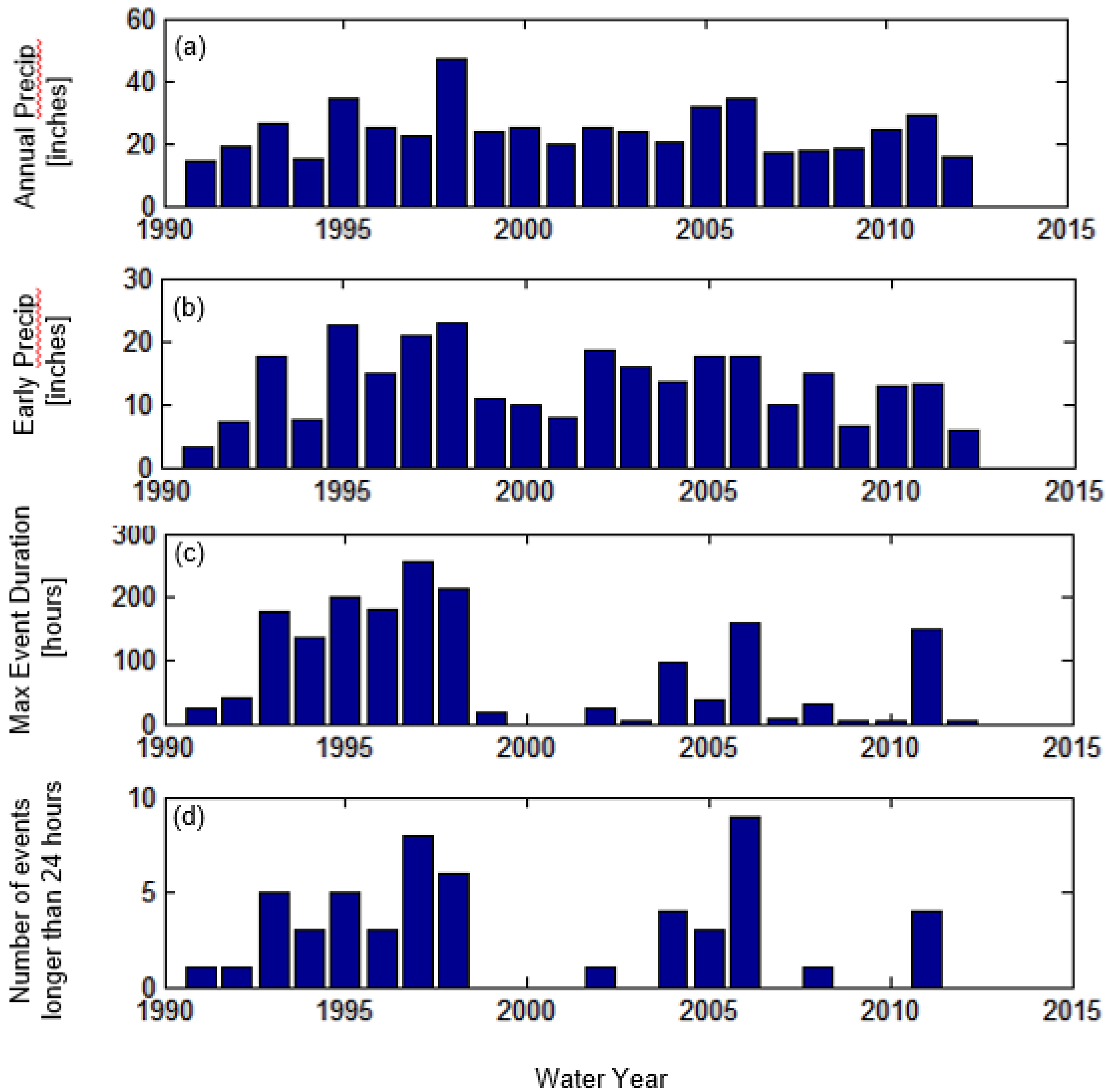

Figure 9: Variation by water year (October 1 – September 30). (a) Total annual precipitation; (b) Total precipitation in October through January; (c) Maximum duration of stratification event (threshold of 0.75 psu) for the water year; (d) Number of stratification events longer than 24 hours in the water year.

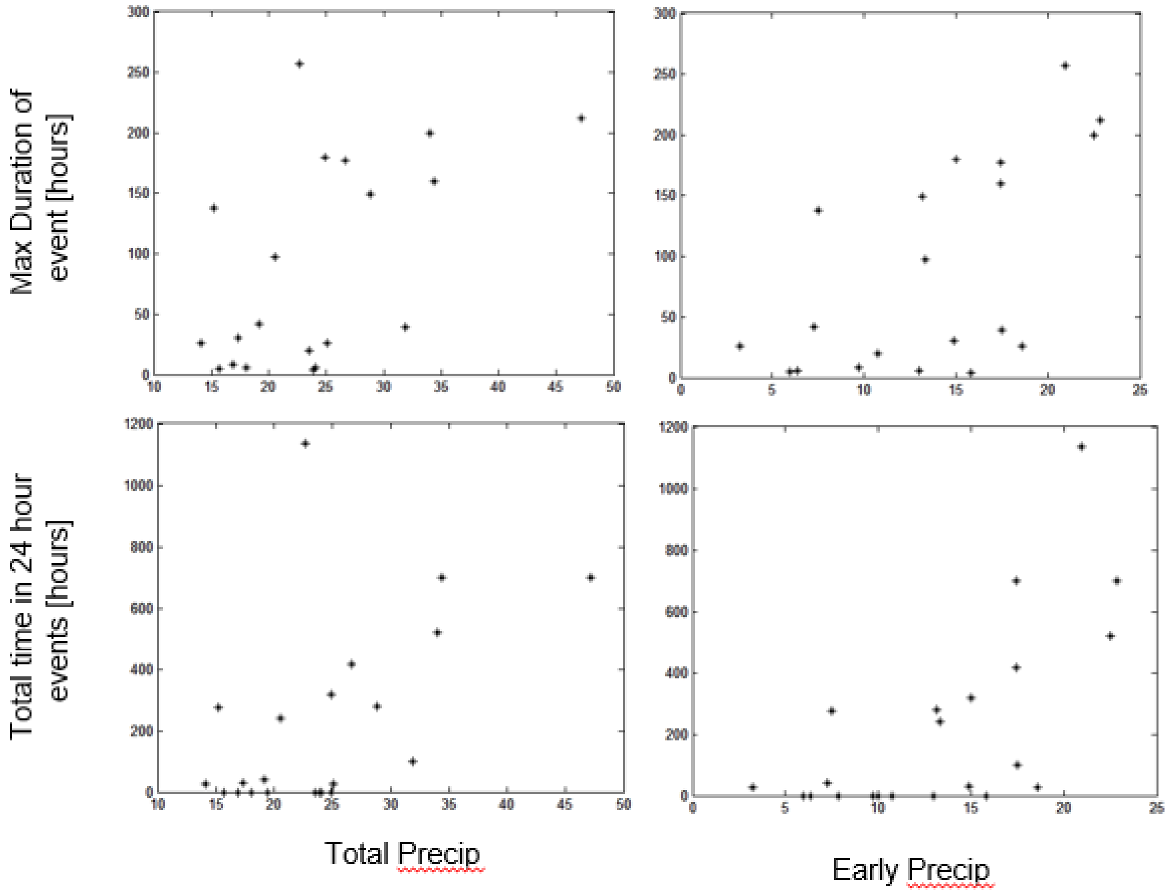

Figure 10: Preliminary evaluation of drivers for South Bay stratification. Candidate drivers (Total Water Year Precipitation and Early Season Precipitation) are on the horizontal axes; Response metrics (Maximum event duration and total time in stratification events) are on the vertical axes.

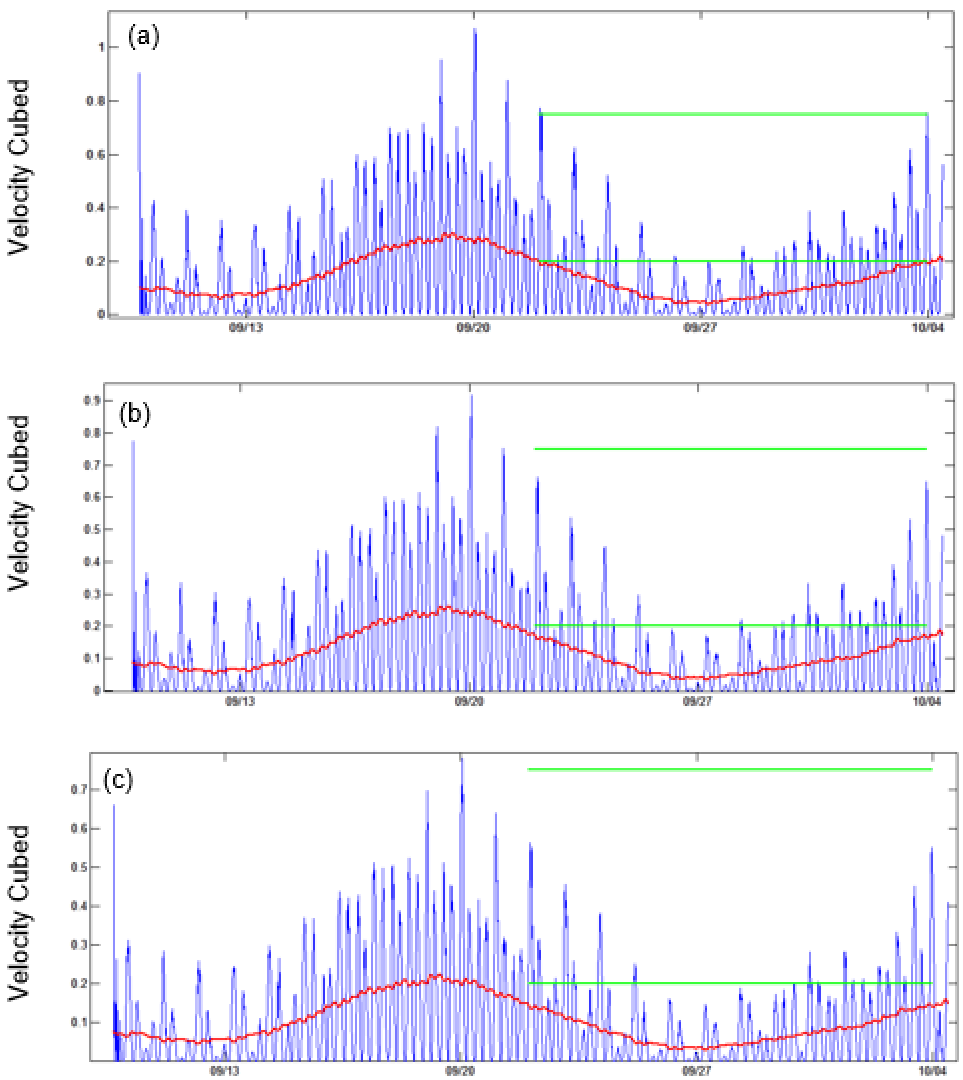

Figure 11: Schematic of effects of reduction of tidal velocities. Blue line is (absolute value of) velocity cubed at San Mateo site; Red line is tidally-averaged velocity cubed. Green bars show 12 day event (approximately the 10 year event under current conditions). In panel (a), current conditions are shown. In panels (b) and (c), the vertical position of the green bars represent the relative level of buoyancy forcing under a 5% and 10% reduction in tidal energy, respectively.